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Wide Range Aerosol Classifier

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WIDE RANGE AEROSOL CLASSIFIER

by

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The purpose of this project was to design, construct, calibrate, and field test a mobile ambient particulate matter sampler (Wide Range Aerosol Classifier) to collect size-classified samples of large aerosol particles. The sampler design was based on a similar stationary sampling system previously constructed by the Principal Investigator, Dr. Dale Lundgren.

The sampler is fitted into a trailer and consists of a large, high flowrate inlet from which 5 isokinetic samples are withdrawn. Four of the samples are passed through single stage impactors with different cutpoints while the fifth is passed through a total particulate matter filter. The 4 impactors were designed to collect particles greater than 7.5 mm, 15 mm, 30 mm and 60 mm diameter. Aerosol particles smaller than 7.5 μm are sized by using separate lower flow rate cascade impactors following the last single stage impactor.

An accompanying analysis lab was set up in a mobile van. Analysis equipment includes an analytical balance and a sample equilibration chamber.

The mobile sampler was briefly field tested in Gainesville, Florida.

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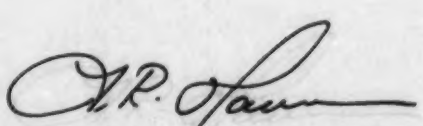
FOREWORD

The Environmental Monitoring Systems Laboratory (EMSL) has established a nationwide Inhalable Particulate Network to provide data to support a proposed revision of the existing particulate standard. In order to better understand the source-receptor patterns apparent in the data and the quality of relationships between samplers, research tools have been developed which provide additional characterization of suspended particles. One such tool is the Wide Range Aerosol Classifier (WRAC) developed for EMSL under cooperative agreement with the University of Florida. This research sampler accurately size fractionates the entire spectrum (0-200 μm) of suspended aerosol mass to provide extended range ambient size distributions. These size distributions, when compared with the results of colocated routine monitors, assists EMSL in determining the quality of the data collected. In addition, EPA's Office of Air Quality Planning and Standards has found these distributions very useful for determining the impact of fugitive dust on the existing particulate standard. The report which follows describes the concept, design and operation of the WRAC.



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This report is submitted by the Department of Environmental Engineering, University of Florida, in fulfillment of United States Environmental Protection Agency grant number R-806714-010. This report covers the total project period from October 1, 1979 to November 30, 1980.

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SECTION 1

INTRODUCTION

The United States Environmental Protection Agency (EPA) has based the air quality standards for particulate matter upon the total amount of suspended particulate matter collected by the reference method, a high volume air sampler (1). This sampler has been assumed to collect particles less than ~100 μm diameter (Stokes equivalent) (1). Test data obtained by Wedding, McFarland, and Cermak (2) indicate, however, that the sampling efficiency of the high volume air sampler may be as little as 7 percent for 50 μm particles and 18 percent for 30 μm particles in moderate winds. The high volume air sampler is also sensitive to orientation, showing a 20 percent drop in collection efficiency for particles 15 μm in diameter and larger with a 45° shift in wind direction. Because the mass of a particle increases as the cube of its diameter, the mass concentrations measured by the high volume air sampler can also vary widely.

The EPA in 1979 tentatively defined inhalable particles (I.P.) as those less than 15 μm, and has considered establishing a fine particle standard consisting of particles less than ~2 to 3 μm diameter. Currently, the EPA is considering the I.P. upper size limit at 10 μm. Consideration of an I.P. standard has generated interest in defining the total atmospheric particle size distribution. Only then will it be possible to determine what fraction of

the total atmospheric aerosol is being collected and what fraction would be desirable to collect by existing or proposed sampling devices.

In a previous paper, Lundgren and Paulus (3) described a stationary sampling system which effectively sampled large atmospheric particles (up to ~100 μm), determined the large particle size distribution and total atmospheric mass concentration, and compared their results with collection by dust fall plates and with a standard high volume air sampler. That study provided the background for the present project to design, construct, and field test a mobile sampler for sampling large atmospheric particles. With this sampler it should be possible to characterize the particle size distribution at field locations in the continental United States, and to compare the results with simultaneous and historical total suspended particulate (TSP) high volume air sampler data and with inhalable particulate matter data. Details of this project are described in this report.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The results of limited field testing indicate that the Wide Range Aerosol Classifier (WRAC) can be easily set up at a suitable field location and operated to collect 24-hour samples of atmospheric aerosols. The accompanying analysis van can be used to prepare, condition, and weigh the collected aerosol samples. The collected samples can be used to determine an aerodynamic particle size distribution based upon the mass of the ambient aerosol.

Calibration tests indicate that single-stage impactors do not collect particles as small as originally calculated. However, the classification is adequate to provide a good characterization of the atmospheric aerosol. In addition to the single-stage impactors, a high volume cascade impactor is used to classify particles in the 1 to 10 μm size range.

It is recommended that the Wide Range Aerosol Classifier be operated at important sites in the United States in order to directly obtain ambient particle mass distribution data.

SECTION 3

LITERATURE REVIEW AND DESIGN CONSIDERATIONS

LITERATURE REVIEW

Many researchers have investigated the size distribution of atmospheric aerosols. Although only a few of these studies have sized particles larger than 10 μm diameter, several have reportedly shown a multimodal distribution.

Noll and Pilat (4) used a rotating arm with 16 rectangular collector plates. The collection surfaces were coated with Vaseline® and collected particles greater than ~10 μm diameter. A change in slope of normalized number concentration was noted for particles between 60 and 80 μm diameter. Woodcock and Mason (5) collected salt spray aerosol over the ocean on glass slides attached to wind vanes. Okita (6) used sedimentation and web threads to collect particles. Jaenicke and Junge (7) used a propeller type inertial impactor to collect particles greater than 10 μm. Lundgren and Paulus (3) used the large diameter inlet, high flowrate sampler, on which the WRAC was based, to efficiently collect and size particles up to 100 μm diameter. A biomodal distribution was reported. Hinderman, Hobbs, and Radke (8) conducted an airborne study of aerosol particles emitted from a papermill. Particles between 5 and 90 μm diameter were impacted directly on slides. They also used a rapid expansion chamber, an Electrical Aerosol Analyzer, an optical particle

counter, and an axially scattering spectrophotometer to size particles between .002 and 30 μm diameter. A multimodal size distribution was reported. Using the same equipment, Radke et al., (9) conducted an airborne study and sampled aerosol particles from a forest fire. A range of 0.01 μm to 60 μm was reported with a multimodal distribution.

Lee (10) collected atmospheric particles with a NASN modified Andersen 5-stage impactor. Whitby et al. (11) point out that Lee's data can be best fit with a bimodal curve.

Whitby, Husar, and Liu (12) reported on samples of L.A. smog collected by the MAAS sampler, a mobile sampling van which combines an Electrical Aerosol Analyzer and an optical particle counter. They reported a bimodal particle size distribution.

INLET DESIGN CRITERIA

The basic problem in measuring large atmospheric particles is transporting a true or representative sample of these particles into a measurement device. This difficulty is particularly serious for the collection of particles larger than ~30 μm diameter because of their great inertia and high settling rate.

Particle settling velocity (Vs) is determined by a balance between the force of gravity acting on a particle and the fluid drag force exerted by the medium through which the particle falls. Simply put, settling velocity

increases rapidly with increasing particle size. Sampling tube inlets which are pointed upward will capture a greater proportion of large particles than are in the actual distribution due to the settling of the particles into the inlet. The increase in the relative number of large particles sampled is equal to $1 + [Vs/Vo]$, where Vo equals the sampling tube inlet velocity (13). Davies (14) points out that the error can be kept reasonably small if the inlet velocity (Vo) is made several times greater than the settling velocity (Vs) of the largest particle desired. He suggests that a Vo of 25 times Vs would give a permissible error of only 4 percent overestimation for a tube pointed upward. The present system meets these criteria for a 55 μm diameter particle. These criteria predict an 11 percent overestimation for a 100 μm diameter particle.

Particle inertia is a function of particle mass. From Newton's first law, where force equals mass times acceleration, a larger force is required to accelerate (or decelerate) a larger (heavier) particle as quickly as a smaller (lighter) particle. Because the size of a particle also effects the drag it experiences from the air, the relaxation time (τ) is used as an indication of its ability to accelerate or decelerate. Fuchs (13) defines particle relaxation time (τ) as: $\tau = D_p^2 p/18\eta$, where D_p is the diameter of the particle, ρ is its density, η is the viscosity of air, and τ has units of time.

It is also convenient to define a particle stopping distance, ℓ, as the distance a particle will travel when decelerated in a fluid medium (air) from an initial velocity (V) to rest. Fuchs (13) has shown that $\ell = V\tau$.

Davies (14) uses ℓ to evaluate the effect of particle inertia on sampling efficiency for 2 situations. When sampling at a known inlet flow rate (Q), a suction velocity (Vx) will be produced which is a function of the distance from the inlet orifice. Davies examines the case where Vx is evaluated at a distance ℓ from the center of the orifice. He uses the equation $Vx = Q/4\pi\ell^2$ where Q is the flowrate of the sampler inlet and $4\pi\ell^2$ is the surface area of a sphere of radius ℓ.

More appropriate might be the equation determined empirically by Dalle Valle (15) from measured velocity contours of exhaust hoods. For a point at a distance ℓ along the center line from the hood face, $Vx = Q/10\ell^2+A$, where A equals the inlet face area. Davies reasons that if the radius of the inlet (R) is several times larger than ℓ, then the effects of inertia will be negligible (14).

Davies also has examined the situation of sampling in a cross wind with some velocity (Vw) and has reasoned that the inlet radius (R) should be much greater than the stopping distance associated with the wind (i.e., $\ell = Vw\ \tau$). Davies has suggested that the inlet radius, R, should be at least 5ℓ. For the mobile sampler, the condition that $R = 5\ell$ requires that ℓ be less than 6 cm. At a distance of 6 cm from the inlet orifice, the maximum velocity using the latter equation would be 2 m/s (~ 4.5 mph). The stopping distance for a 100 µm diameter particle at this velocity is 6.15 cm. This nearly meets Davies' criteria and suggests that the mobile sampler inlet is dimensionally adequate to efficiently sample 100 µm diameter particles in winds up to ~2 m/s (4.5 mph).

Several researchers have noted that Davies' theoretical criteria seem overly restrictive for efficient sampling (16), and that his criteria are not met by several commercially available instruments (17). Agarwal and Liu (18) did a theoretical study of sampling efficiencies taking into account both particle inertia and settling. They determined the flow field around a vertical thin walled inlet from the Navier-Stokes equations and then calculated particle trajectories. They determined a critical particle trajectory which is a distance, Rc, from the inlet axis, such that particles inside this radius enter the inlet. Sampling efficiency was calculated by comparing the concentration of particles entering the inlet versus the actual concentration of the air sampled.

Agarwal & Liu noted that the sampling efficiency was a function independently of both the Stokes number ($Stk = \frac{\rho C D_p^2 V_o}{9\eta D}$) and the relative settling velocity ($V_s' = V_s/V_o$). The characteristic length and velocity are the inlet diameter, D, and the inlet velocity, Vo. Their research indicates that if the product (Stk)(Vs') is less than 0.10, then sampling efficiency will be greater than 90 percent. Agarwal and Liu caution, however, that their criterion for efficiency regards all particles which enter the inlet as sampled, whether or not they impact and possibly stick on the inside wall of the inlet. The value of (Stk)(Vs') for the sampling of 100 μm particles with the mobile sampler is 0.025. Solving for particle diameter with (Stk)(Vs') equal to 0.10 indicates that the mobile sampler can sample particles as large as 130 μm diameter with an accuracy of 90 percent. These values assume, however, that Stokes law holds for particles this size.

The shroud of the Wide Range Aerosol Sampler was designed to provide a calm air space around the inlet orifice so that the sampler would be less sensitive to cross winds. To be effective, it must be large enough so that particles will not impact on it but will flow around and over the shroud. To insure this, it should be large in comparison to ℓ.

Using the same ratio of 1:5, this criterion could be met for a particle with a stopping distance less than or equal to 1/5 the diameter of the shroud, or 30 cm. This condition is met for a 100 μm diameter particle in a 9 m/s (20 mph) wind.

CRITERIA FOR METHOD OF SIZE CLASSIFICATION

In designing the Wide Range Aerosol Classifier, consideration must be given to the method of particle sizing. The many methods available were compared against some basic criteria. Since suspended particulate matter measurements are gravimetric, it is desirable that the particle sizing method used also be a gravimetric analysis. The EPA's focus in setting new particulate matter standards is to protect against adverse health effects. The I.P. standards will be set on the basis of what can be inhaled. Therefore, it will be beneficial to have the particles sized according to their aerodynamic properties.

Perhaps the most basic particle size measurement method is to optically size collected particles using a microscope. Particles may be collected on a glass slide or a filter. The lower size limit for a light microscope is

~0.5 μm, or about the wavelength of visible light. Since particles are generally irregular, this type of analysis gives an average or statistical size. This type of analysis is not a good predictor of the particle's aerodynamic behavior because of the particle's irregularities and because the particle's density is not known. Microscopic analysis does not give a direct measure of mass distribution. A volume can be calculated from the statistical size but only an average density can be calculated from the total mass collected and the calculated total particle volume. This process is very time consuming because each particle must be sized and several calculations must be made to put the data in the desired format.

A faster method of optical sizing is to use an optical particle counter. This device measures the amount of light scattered by a particle and compares that intensity with the amount which would be scattered by a known calibration aerosol. Although a particle size and volume can be calculated, this method cannot be related specifically to a particle's aerodynamic behavior. There is also considerable difficulty in sampling large particles with commercially available optical particle counters.

Inertial classification devices, such as impactors, centrifuges, and cyclones are also commonly used. These devices separate or deposit particles based upon the particle's aerodynamic properties or stopping distance. The stopping distance is a function of the particle size, shape, and mass. The particle size determined is then that of a spherical particle of unit density ($1 gm/cm^3$) which has aerodynamic properties equivalent to those of the particles sampled. Centrifuges are mechanically quite complex and not suited to sampling

large volumes of air. Cyclones are less complex than impactors and can handle large flow rates adequately. Impactors have a major advantage over cyclones in that the particles are collected onto a surface which can easily be removed, weighed, and otherwise analyzed. Cyclones collect the particles on their inside wall, making complete removal for weighing difficult. It is for these reasons that an impactor collector was selected to size the atmospheric particles.

IMPACTOR THEORY AND DESIGN

Devices depending on inertial impaction to collect aerosol particles have been widely used and discussed. Since the first cascade impactor was described in 1945 by May (19), many types of impactors have been constructed and used. Fuchs describes several such impaction devices (13). Much effort has been put into evaluating and describing the operation of impactors, and impaction theory is now well developed. Basic operation of an impactor can be described as follows: the sampled aerosol is passed through a nozzle at a known velocity and directed toward an impaction surface placed perpendicular to the nozzle flow. Each particle will possess an inertia dependent upon its mass and the known velocity. Those particles with too great an inertia will have a stopping distance, ℓ, too great to follow the flow streamlines around and past the collection plate and will strike (impact on) the surface. As before, the stopping distance is a function of the jet velocity, Vj, and the particle relaxation time, $\tau(\ell = V_j\tau)$. If the jet velocity is held constant, then the particles are discriminently sampled on the basis of τ. From the definition $\tau = Dp^2\rho/18\eta$, it is seen that τ varies with Dp^2 where Dp is the particle

diameter, ρ the particle density, and η the gas viscosity. This simple analysis assumes the particles are spherical and that Stokes' law applies. An impactor separates particles according to a particle's aerodynamic property (i.e., the stopping distance). This means that the impactor cannot distinguish between small heavy particles and large light particles such that the $Dp^2\rho$ values are equal. In addition, particles are seldom spherical in shape. They may be oblong flat chains, irregular shapes, or agglomerates of several particles. There is also a change in the drag on the particle that is relative to the size of the particle. For simplification this discussion will consider particle size as the equivalent aerodynamic diameter.

The collection efficiency of an impaction device has been found to be closely related to an impaction parameter, $Stk = (2\ell/W)$, where ℓ is the particle stopping distance and W is some characteristic dimension of the system, usually the jet diameter or width. The square root of the Stokes number ($\sqrt{Stk}$) can be considered as a dimensionless particle size. Substituting in the equation for the Stokes number of a rectangular impactor nozzle of width W and length L gives:

$$Stk = \frac{V_j \tau}{W/2} = \frac{2Q\tau}{LW^2} = \frac{2QDp^2\rho}{LW^2 18\eta} = \frac{Q\rho Dp^2}{9\eta LW^2}$$

so that $$\sqrt{Stk} = \sqrt{Q\rho/9\eta L}\ \frac{D_p}{W}$$

The plot of efficiency vs. $\sqrt{Stk}$ is a slightly "S" shaped curve (Figure 1) with the steepness of the curve indicating the sharpness of the

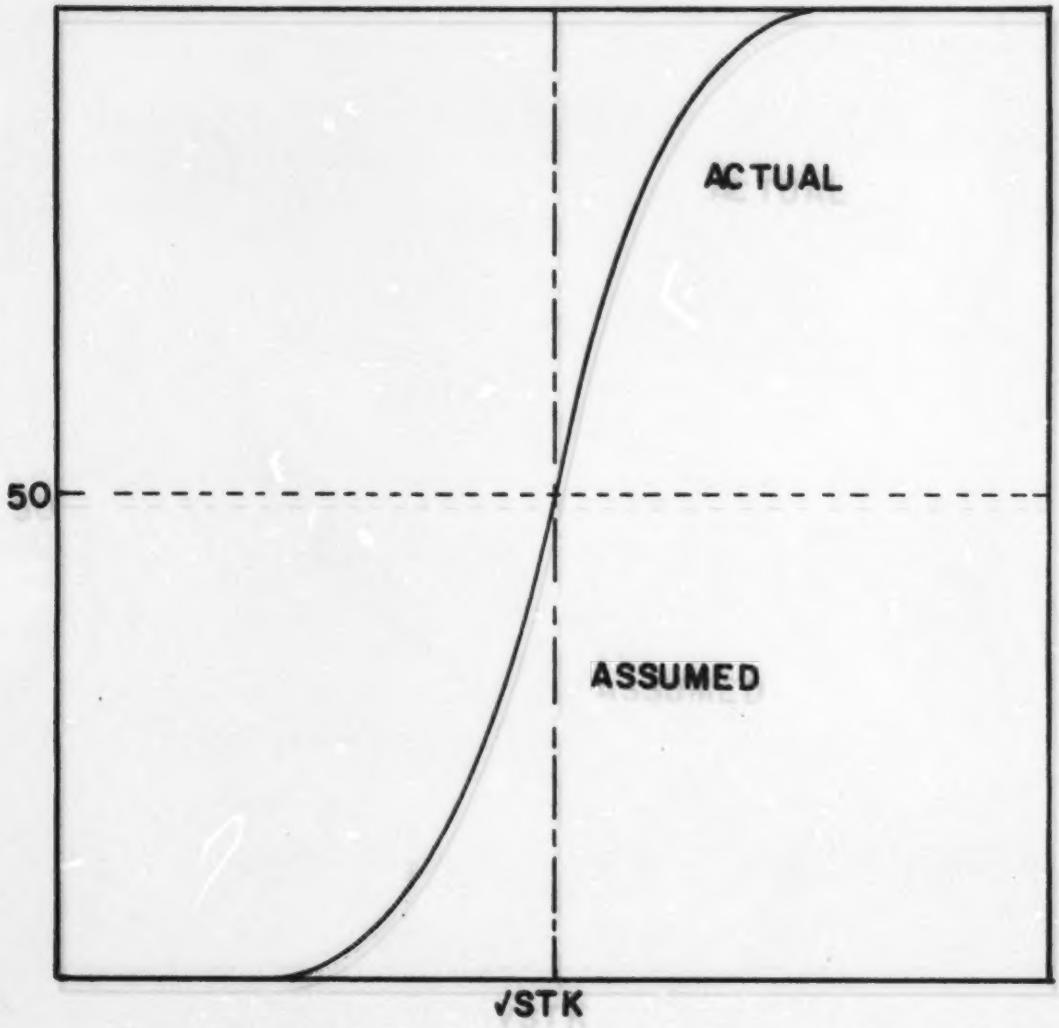

Figure 1. Impactor Collection Efficiency vs. $\sqrt{Stk}$.

impactor cut. General practice is to determine the value of $\sqrt{Stk}$ for 50 percent collection efficiency and use that value for dimensioning the impactor jet.

It is assumed that the mass of the larger particles not collected is approximately equal to the mass of the smaller particles which are collected and that they cancel one another. The impactor is considered to be 100 percent efficient at the $\sqrt{Stk_{50}}$ point. This assumption has proven valid for most cases. The particle size identified at the $\sqrt{Stk_{50}}$ is called the $D_{p_{50}}$, or diameter of the particle at the 50 percent point.

Much theoretical and experimental work has been done to define the effects of various impactor dimensions and characteristics on performance. Marple and Liu (20) examined the effect of jet to plate distances, jet Reynolds number (Re), and jet throat length by numerical methods and compared the results with experimental data. Their criteria were used in the design of the 4 impactors.

The impactors for the sampler were designed and constructed as single-stage rectangular jet impactors. There is an advantage to using several single-stage impactors in parallel when sampling large particles because of the high wall losses for large particles in cascade impactors. Another advantage is that the total amount of air sampled can be greater because each impactor samples only a fraction of the total. Thus, the mass collected can be greater for a given sampling time allowing greater sensitivity in weighing. There is also a difference in data reduction. In a cascade impactor, the weight gain (or equivalent measure) on each stage represents the mass of particles between

two specific size ranges. With parallel single-stage impactors, each stage collects all particles greater than a given size so that the differences between size ranges may be obtained by subtracting one stage gain from another.

Using the design curves presented by Marple and Liu is quite simple. For a rectangular jet impactor, both the jet velocity (Vj) and the Stokes number (Stk) can be expressed in terms of the jet width (W) provided the flow rate (Q) and the jet length (L) are known.

The flow rate is limited by the operating range of the high volume blower, and was set at 1.56 m^3/min (55 cfm). The slot length was determined by the size of the filter holders as 17.8 cm. Solving for the velocity and Re:

$$Vj = Q/LW = \frac{1.46}{W} \text{ cm/s}$$

$$Re = \frac{2\rho VjW}{\eta} = \frac{2Q}{\eta L} = 21{,}000$$

From the curve presented by Marple and Liu, $\sqrt{Stk_{50}} = 0.675$. Marple and Liu examined the effect of changing the distance from the impaction plate to the jet. This jet to plate distance, S, is generally expressed as a dimensionless ratio of the jet width, hence, S/W. They compared their theoretical findings with experimental points taken from data presented by Mercer and Chow (21) and by Mercer and Stafford (22). It appears that there is a considerable variation in $\sqrt{Stk_{50}}$ with the jet to plate distance if $S/W < 1.5$ for rectangular jet and $S/W < 1.0$ for circular jets. There is very little change with S/W if S/W is greater than these values. It was decided that an

S/W of 2 would be used in the present system so that slight verticle changes in the impactor plate location would not produce noticeable changes in the results.

Marple and Liu's curve for $\sqrt{Stk}$ vs. efficiency for Re = 25,000 is for S/W = 1. They do, however, plot efficiency vs. $\sqrt{Stk}$ for various S/W values at Re = 3,000. The value of $\sqrt{Stk_{50}}$, at Re = 25,000 and S/W = 1 was multiplied by the ratio of $\sqrt{Stk_{50}}$ at S/W = 2 over $\sqrt{Stk_{50}}$, S/W = 1 shown for Re = 3,000.

From the value of $\sqrt{Stk_{50}}$, S/W = 2, Re = 25,000, the equation:

$$Stk = \frac{Q\rho Dp^2}{9\eta LW^2} = \frac{Qp(Dp_{50})^2}{9\eta LW^2}$$

can be solved to find the value of W necessary to separate out particles larger than DP_{50}. Since Re is not dependent on W for rectangular impactors of equal length, it stays the same for all 4 impactors as does the value of $\sqrt{Stk_{50}}$. Thus, merely by substituting the desired value of DP_{50} the appropriate value of W can be found.

SECTION 4

CONSTRUCTION OF SAMPLER

INTRODUCTION

The sampler was designed to be built into a 4.9 m (16 ft) Avion trailer provided by the EPA. The mobile sampler design was based upon a stationary sampler previously constructed by the Principal Investigator. The conversion to a mobile sampler introduced several design considerations. The primary constraints were that the equipment be light, easily assembled and disassembled, readily repairable, and fit into the trailer with sufficient working space to allow for its operation. It must also have been sturdy enough to withstand several years of cross continental transport, high wind loads, and other environmental stresses when set up and operating.

TRAILER MODIFICATIONS

It was necessary to make several modifications to the trailer to accommodate the sampler system. All counters in the rear of the trailer were removed to make room for the sampler and blowers. A load bearing deck was constructed on top of the trailer. The sampler design required a large diameter inlet and an even larger diameter shroud erected on top of the trailer. In addition to the dead weight of the inlet and shroud, there is a

considerable wind load on these pieces. Personnel stand on the roof deck to erect or disassemble the sampling inlet. Also, it was decided that the air plenum and the size-selective samplers should be supported from the roof deck to leave more free space inside the trailer.

Since all of the weight must ultimately be supported by the main frame, it was calculated that 5 cm diameter steel pipe should be secured to the frame as columns to support the deck. Negative loads were also considered because of the possibility of heavy wind loads or severe road jolts. The pipes were secured by two flanges which were bolted to main frame members. The pipes screw into the flange and extend through the roof of the trailer.

The 8 steel pipe columns were installed on the 2 symmetrical longitudinal frame members of the trailer (4 columns on each side). Columns were placed in front and in back of the trailer and at 2 interior positions, ahead of the door and behind the axle. The deck was constructed of pressure treated lumber because of its weatherability and workability.

Since all of the overhead weight must rest on the columns, the main members in the deck are the extreme outside sections which are connected to the columns. The deck consists of two 5 cm x 25 cm boards which extend the length of the trailer and are bolted to the columns. Boards 5 cm x 15 cm are used at each end and on either side of the sampler inlet. The remainder is constructed of 5 cm x 10 cm lumber.

The trailer was completely rewired inside utilizing only the existing external connector and electrical panel box. The sampler requires 35 amps of 220 volts service. Both auxilliary blowers and the 5 high volume blowers are switched individually.

INLET AND SHROUD

The large inlet and shroud are integral design components. The large diameter of the inlet facilitates the capture of large particles. The large shroud acts as a wind break and provides a calm air space around the inlet.

The inlet must remain fairly rigid and circular and resist wind loads. The inlet is 60 cm in diameter and is constructed in 3 sections from 16 gauge galvanized steel rolled to size and welded. The inlet consists of 2 removable sections each 90 cm long and a 30 cm long, pemanently attached section. The sections have welded flanges and are bolted together with a gasket seal. When disassembled, the sections can be lashed to the trailer deck.

The 30 cm section is permanently fixed in place through a hole cut in the trailer roof. It connects the inlet tube to the air plenum. The entire inlet tube and the air plenum with the samplers is supported by the trailer deck.

The shroud is 152 cm in diameter and is 122 cm high. It is constructed from .064 cm aluminum sheet which has been "textured" to increase its rigidity. The shroud is constructed in 4 sections. Each section of the aluminum sheet is riveted to two 122 cm x 3 cm bands of rolled aluminum, 0.32 cm thick. The

bands are rolled on a 76 cm radius. A 91 cm long piece of angle iron is fastened to the 4 aluminum posts which support the shroud by bolting the angle iron to the posts. The shroud extends approximately 60 cm above and below the inlet opening. The sections of the shroud are designed such that sections 2 and 4 overlap sections 1 and 3 at the posts, so that the outside is smoother. The posts are bolted to the deck at the bottom and bolted to the deck railing in the middle. The rail is supported by the 5 cm steel columns and is reinforced to resist the wind loads on the shroud. The sections of the shroud and the support posts can be disassembled and either stored on top of the trailer or inside the trailer.

A rain shield has been designed for use when the sampler is operating. It consists of a 90 cm flat disk supported 30 cm above the top of the shroud and centered above the inlet. It prevents rain from falling directly down into the inlet under light wind conditions. A wind-driven rain should fall at an angle and impact on the side of the tube. From there it should run down the side and into the air plenum box and not into the samplers. Preliminary field sampling has shown this to be true for light rainfall.

SELECTIVE SAMPLER

The size-selective sampler inlets were designed to extract isokinetic samples from the air flowing through the inlet tubes. The samplers are constructed of 0.10 cm aluminum bent to shape and riveted together. The sampler inlets are of equal area so that an equal volume of air can be sampled through each sampler. The impactor inlets measure 17.8 cm x 6.55 cm.

Inlet area is determined by the slot width required for the first impactor; therefore the Number 1 impactor is a straight nozzle (neither converging nor diverging).

The selected dimensions for the single-stage impactors are based on several factors. In order to collect a significant amount of particulate matter, a high flow rate is desired. Standard high volume air sampler are readily available, so it was desirable to utilize them. The impactors are designed to mount directly on top of a high volume filter holder. The free filter area of the filter holder is 17.8 cm x 22.9 cm.

To minimize losses and facilitate construction, a rectangular jet design was used. The impactors were designed with the jets 17.8 cm long in order to leave more room for the air flow over the impactor plate to turn down into the filter. This reduces the particle losses on the wall of the impactor.

The jet width for each impactor was determined using the method previously described. Assuming a flow rate of 1.56 m^3/min (55 cfm) and a jet length of 1.78 cm, the Reynold's number for the impactor nozzle was calculated. Using this Reynold's number the value of an impaction parameter ($\sqrt{StK}$) can be determined from the impactor efficiency curves presented by Marple and Liu (20). Using this $\sqrt{Stk}$) value, the jet width W was calculated for each desired particle collection size. The calculated $D_{p_{50}}$ values for impactors 1, 2, 3 and 4 were 60, 30, 15, and 7.5 µm, respectively.

Care must be taken in construction of the impactors. The jet widths were constructed to be within 5 percent of the design width and have parallel sides.

The fifth sampler, which collects a total particle sample, was designed with a square inlet so that it would fit better between the impactor inlets. The sides of all the sampler inlets are straight to reduce any loss of particles onto the walls. The fifth sampler's inlet area is the same as for the other samplers.

An additional advantage of using high volume air sampler blowers is that flow controllers are readily available on the market. These flow controllers insure a constant flow rate through the sampler so that the total air volume for the sampling period is known and so that a representative sample is drawn for each hour over the normal 24-hour sampling period. Therefore, if the total sampling time is known and the flow rate is known and constant, the total air volume sampled is known. Aerosol mass concentrations can then be computed. A constant flow rate is additionally critical for impactors because the aerosol impaction efficiency is a function of the flow rate through the impactor. If the flow rate is not held constant, the size of particles collected will vary, decreasing the quality of that sample.

A hot-wire anemometer is used by the flow controller to sense the air flow rate through the filter holder. A voltage regulator is connected to the anemometer and is used to control the motor speed. The flow controller can adjust the high volume air sampler over a range of flow rates.

It is desirable that additional particle size data be obtained by adding a high flow rate cascade impactor after a single-stage impactor. Several cascade impactor units, such as those available from Sierra Instrument Company, are designed to fit directly onto a high volume sampler filter holder. As used in this application, they will allow particle size classification down to ~1 μm. Placing a cascade impactor after a single-stage impactor would reduce the errors normally caused by large particles which can bounce off the first impaction plates and get caught on lower plates or on the final filter.

AIR PLENUM AND AUXILIARY BLOWERS

In order to achieve the high flow rate through the inlet, 2 large auxillary air blowers are used to exhaust 15.6 m^3/min (55 cfm) each. With the 5 particle samplers operating at 1.56 m^3/min (55 cfm), a total flow rate through the inlet of 39 m^3/min (1380 cfm) is achieved.

The bottom of the inlet tube is connected to an air plenum. The particle sampler inlets extend up through the plenum box into the inlet tube. Excess air that is not sampled is pulled past the particle sampler inlets, through a filter, and out of the air plenum by the large air blowers, which exhaust the air out the bottom of the trailer.

The air flow rate through the auxilliary blowers is measured using thin plate orifices installed in the ducts between the blowers and the plenum box.

These orifices were designed and constructed according to standard practice and were calibrated in place against pitot tube probings of the ducts (Figures 2 and 3).

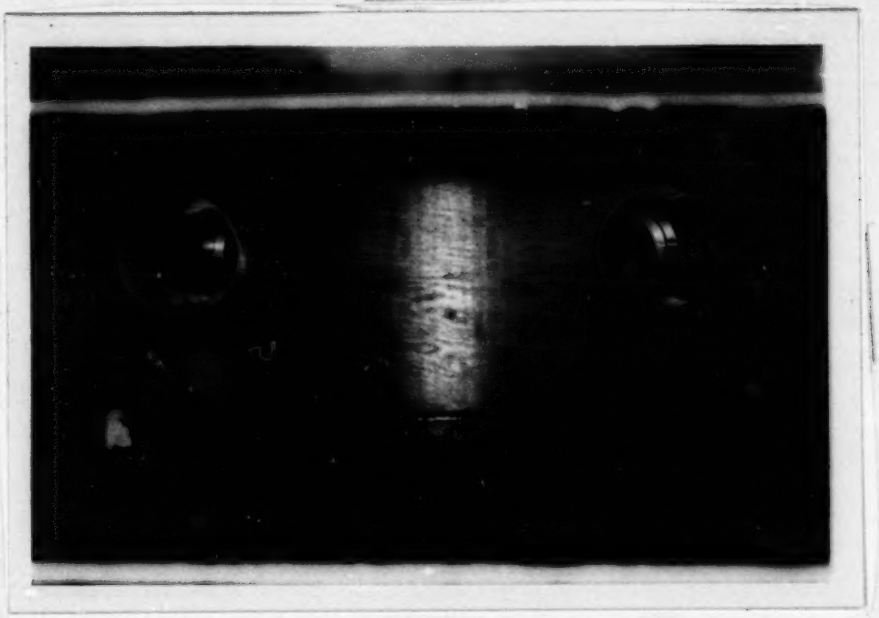

Figure 2. Inside the air plenum, ducts for the auxiliary blowers showing the thin plate orifices.

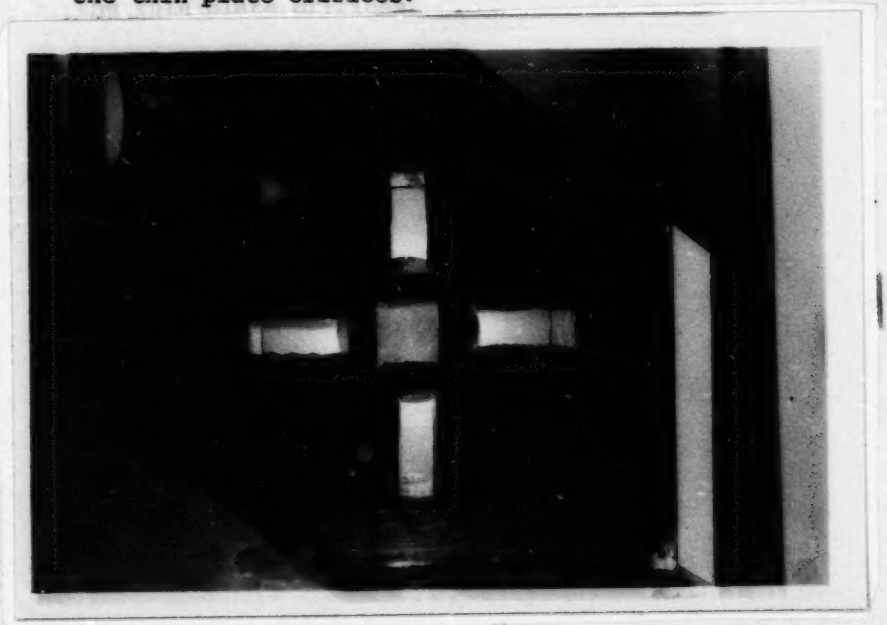

Figure 3. Inside air plenum, positioning of the sampler in the inlet.

SECTION 5

FIELD TESTING AND CALIBRATION

FIELD SITE

The mobile sampler was field tested at a site on the boundary of the Gainesville Regional Airport. The site is used by the Solar Energy section of the Mechanical Engineering Department of the University of Florida to house experimental apparatus; it was chosen because electrical power was readily available and because the sampler could be left set up on the site for as long as necessary. A chain link fence enclosing the site ensured security of the sampler.

The site is level and is clear for at least 9 m around the sampler. There is a 1-story building on the site and trees on 2 sides. The Airport borders the site and is clear. This site is approximately 11 miles northeast from the University of Florida.

The only major activity in the sampler site area is that associated with the Airport. Gainesville Regional Airport has regular scheduled flights by Eastern Airlines and Air Florida. There is also a general aviation facility which has many private and business aircraft operations. An industrial park is located north of the site. The main industries at the industrial park consist

of a beer distributer, and a small chemical plant. The site is ~1.4 km east of Waldo Road, a major inter-city thoroughfare. None of these activities was expected to contribute significantly to the particulate matter sampled.

FIELD OPERATION

The mobile sampler was towed to the site and erected. The electrical umbilical cord was connected to an available power box. Several samples were collected and analyzed at the university because the Mettler He-20 analytical balance was not functioning properly. After the balance was repaired, the analysis van with the balance was moved to the field site. To reduce vibration, the van was blocked at its corners. In addition, a vibration dampening platform was used under the balance.

RESULTS

Data were collected for 5 days. It was demonstrated that the mobile sampler could be set up in the field and collect samples which could be analyzed in the van. Several problems were noted in operating the sampler. One problem was that insects were collected by the sampler and trapped by the greased impaction plate surface coating. Insects could be removed from the filters but when they were removed from the impaction plates the grease coating would be removed with the insect. Also, some insect parts would remain on the plate. Two possible solutions to this problem would be to use a screen around the air inlet or to use fiber filter media on the impactor collection plate substrate.

A second problem was associated with the collection surface equilibration chamber constructed in the van. In order to accurately weigh the samples, the entire van must be maintained at an appropriate temperature and relative humidity. When the plates and filters are removed from the chamber to be weighed, they will change weight if the conditions in the van are not the same as in the chamber. It is recommended that the van door be opened as infrequently as possible before and during weighing, and that re-weighings be done near the same time of day as the initial weighings to minimize temperature differences.

IMPACTOR CALIBRATION

The 4 single-stage impactors were calibrated in the laboratory to determine their particle size collection efficiency. Each impactor was calibrated by sampling particles of a known size dispersed into the air stream entering the impactors. Impactor collection efficiency was determined by comparing the particle mass collected on the impactor plate with the total mass collected on the plate plus that collected on an after filter. Collection efficiency (E) was then plotted as a function of $\sqrt{Stk}$. Calibration data indicate that the actual impactor efficiency is significantly less than anticipated and that these large impactors do not perform according to the impactor collection efficiency curves developed by Marple and Liu (20).

Calibration aerosols included Pecan, ragweed, and paper mulberry pollen, puff ball spores, and glass beads. Pollens and spores were used because they

are approximately spherical and are nearly mono-disperse. Glass beads, while nearly spherical, are not as mono-disperse as the pollens.

The pollens, spores, and glass beads were sized using a light microscope. The density of the pollens and spores was determined by observing their buoyancy in fluids of varying densities. There is some confusion concerning the size and density of dry pollens and spores. Some sources quote their size and density in a wet condition (23), while others (24) do not.

Small amounts of the particles were dispersed into a mixing chamber using a squeeze bulb and an "S" shaped tube. The bends in the tube break up aggregates as they travel through the tube. A mixing chamber was attached above the impactor inlet to evenly distribute the test particles in the airstream. Particle bounce was minimized during the calibration by using greased collection surfaces and moderate concentration loadings. The impactor after filter holder was connected by ductwork to an air plenum fitted with 3 high volume air blowers. A variable resistance voltage regulator was used to adjust the air flow. One, 2, or 3 blowers were used to achieve the desired flow rate. A thin plate orifice installed in the duct was used to measure the air flow rate.

The collection efficiency data obtained for the impactors were plotted as a function of log $\sqrt{Stk}$. Data for impactor Number 4 were not used due to excessive scatter. However, the calculated $\sqrt{Stk}$ was applied to impactor 4 based on the original impactor design considerations. The data for impactors 1, 2, and 3 all fell on a fairly well defined curve. Data for impactor 4 showed much greater scatter (Figure 4). One possible explanation for this

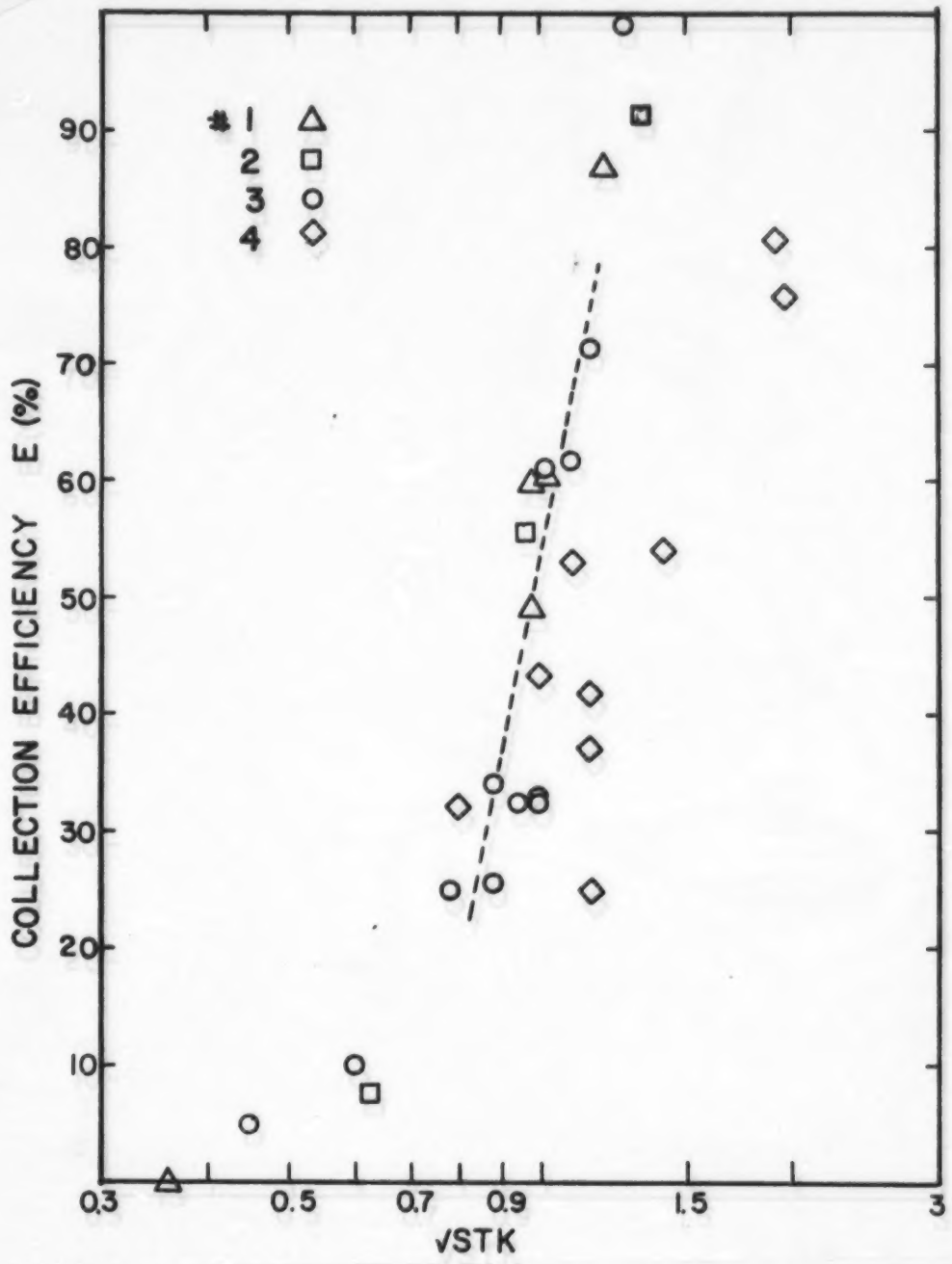

Figure 4. Calibration data for impactors 1, 2, 3, and 4.

increased data variability is that the jet width of impactor 4 is not as close to parallel on a percentage basis as the other impactors. Collection efficiency is strongly dependent on jet width and this relative variation could account for some of the data variability.

Collection efficiency data for impactors 1, 2, and 3 were used to determine a line of best fit determined by a least squares analysis for $y = m \log x + b$. Using the curve obtained, the value of $\sqrt{Stk}$ for 50 percent collection efficiency is 0.98. This result is considerably different from the $\sqrt{Stk}$ value of 0.675 predicted from the curves by Marple and Liu (20). The calibration data indicate that these impactors are less efficient collectors than was expected. The value of $\sqrt{Stk} = 0.98$ indicates that the $D_{p_{50}}$'s of impactors 1, 2, 3, and 4 are 70, 42, 22, and 10 μm, respectively, as compared to the design values of 60 μm at normal sampling rates. Data scatter around the line indicate that at $\sqrt{Stk} = 0.98$ the collection efficiency, E, could vary by ± 6.4 percent. This would indicate a variance in the value of $\sqrt{Stk_{50}}$ and, hence, in $D_{p_{50}}$ of ± 4 percent.

An analysis can be made of the possible errors involved in the impactor calibration by examining the terms involved in the Stokes number, ($Stk = \rho Q C D_p^2 / 9W^2$), and estimating the possible error in the determination of each term. Particle density, ρ, was determined by observing its bouyancy in fluids of varying densities. This procedure could produce an error of ± 10 percent from the actual density. The flow rate was determined by measuring the pressure differential across a thin plate orifice. The calculation of the flow rate through the orifice using the orifice size ratio and the measured pressure

differential across the orifice could be ± 1 percent in error. The measurement of the pressure differential could be in error by ± 10 percent. The calibration aerosols were optically sized using a light microscope. Although the test particles are nearly uniform and spherical, the measured optical size will differ from the aerodynamic size, possibly by ± 10 percent. The width of the impactor jets were measured with a micrometer during construction, but cannot conveniently be measured after assembly. The actual width could vary by ± 5 percent. Calculating the possible error in the value of $\sqrt{Stk}$ for the worst case of all errors adding and none cancelling indicates a possible variation of ± 25 percent in the value of $\sqrt{Stk}$. This would give a range for the actual value of $\sqrt{Stk_{50}}$ from 0.74 to 1.23.

SECTION 6

OPERATION OF SAMPLER

SITING OF SAMPLER

Several factors should be considered in deciding on a site for the sampler. The site should have a fairly open terrain, out of the wind shadow of hills or tall buildings. The sampler should not be sited near a large local source of particulate matter which would bias the ambient concentration measurement, unless the measurement aim is to characterize the emissions from that source. A second siting requirement is the need for electrical power. The mobile sampler requires at least 35 amps of 220 volt service for operation with 1 additional high volume air sampler. If the mobile analysis lab (GMC Transmode) is to be operated simultaneously, an additional 30 amps of 220 volt service should be provided. Power cords for the trailer and van are both about 9 m long, so that the trailer and van must be sited at least that close to electrical power. Both cords have connectors which fit into receptacles on the van and trailer (Figure 5). The other ends of the cord may be wired directly to an electrical panel, or a connector can be used.

Because the mobile sampler must run for 24 hours, it is desirable to select a site with reasonable security. The trailer door is lockable and there is nothing on the outside of the trailer which would be readily stolen.

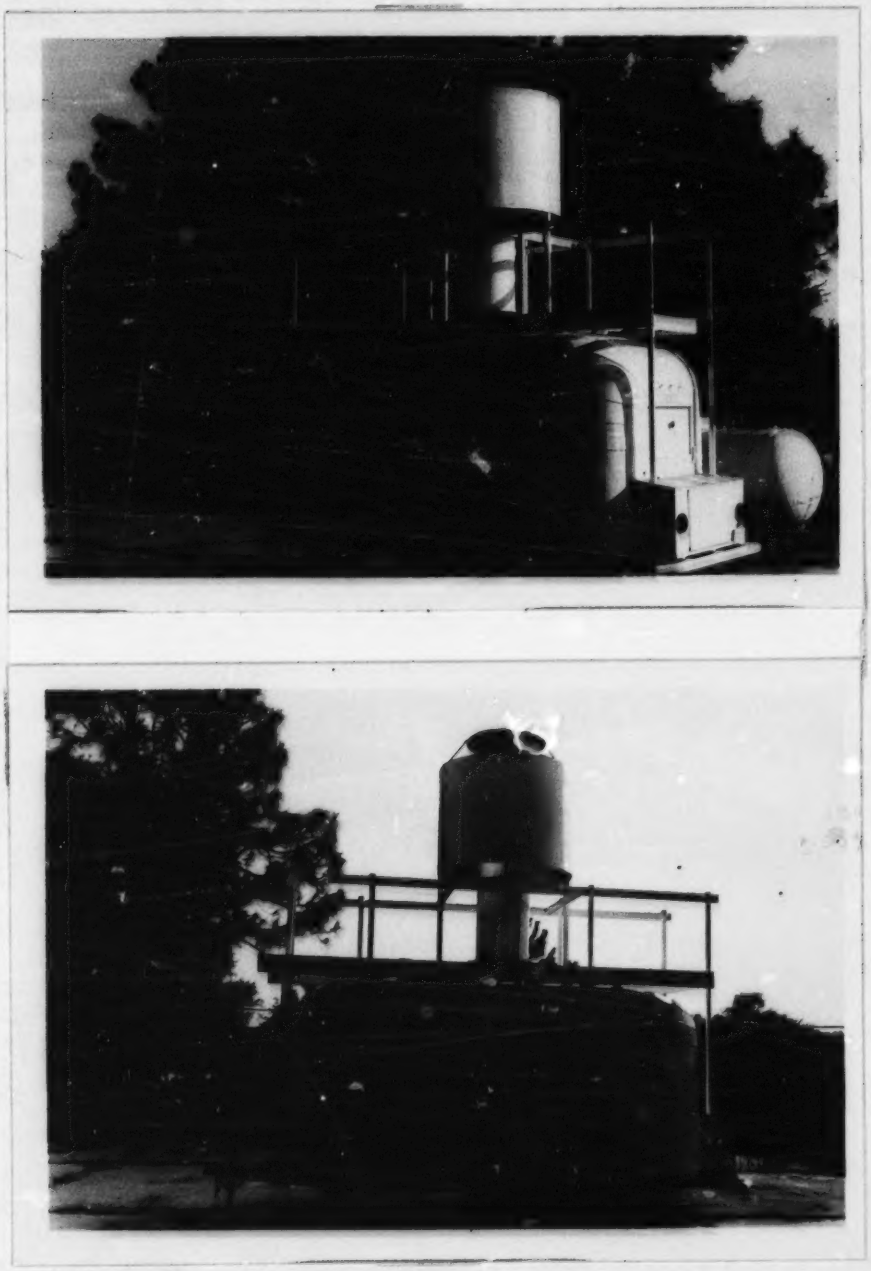

Figure 5. Side views of WRAC.

The trailer could be susceptible to being unplugged from the power source which might produce an electrical shock hazard. Also, the trailer is fairly noisy and should not be sited too near a residence.

SET UP OF SAMPLER

Once the sampler site has been selected, the trailer and van should be leveled and supported by blocks (Figure 6). This increases the stability of both and is necessary for efficient sampling and proper operation of the balance. Concrete blocks should be placed at the corners of the trailer and shims added until the trailer is level and is solidly supported at all 4 corners. A hydraulic jack, level, blocks, and shims are provided for this purpose.

After the trailer is leveled and blocked, erection of the inlet and shroud can begin. The inlet tube should be erected first. Remove the rain cap covering the inlet collar and set inlet tube #1 on top of the collar. Inlet tube #1 has a flange on either end. It should be connected first by placing flange "A" so that the alignment mark corresponds with the alignment mark on the inlet collar (Figure 7). The bolts on the collar flange should align with the holes drilled in flange "A". Place a washer and a nut on the bolts and tighten. Once inlet tube #1 is secured to the collar, place inlet tube #2 on top of tube #1. Inlet tube #2 has only 1 flange and it should mate with flange "B" and tube #1 using the alignment marks on both tubes. Insert bolts through the holes in the flange and fasten with a nut and washer as for Flange "A".

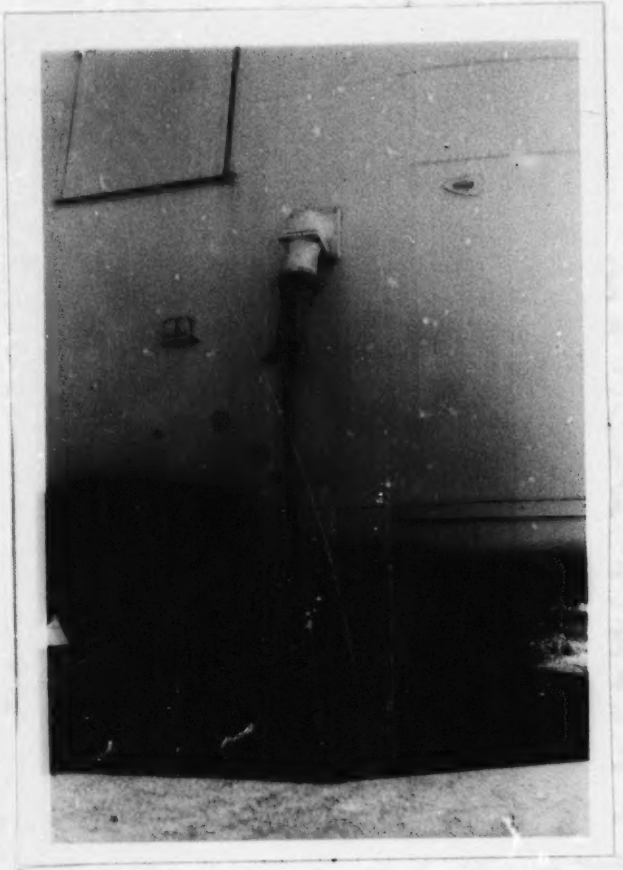

Figure 6. Close up of block and shims on trailer corner.

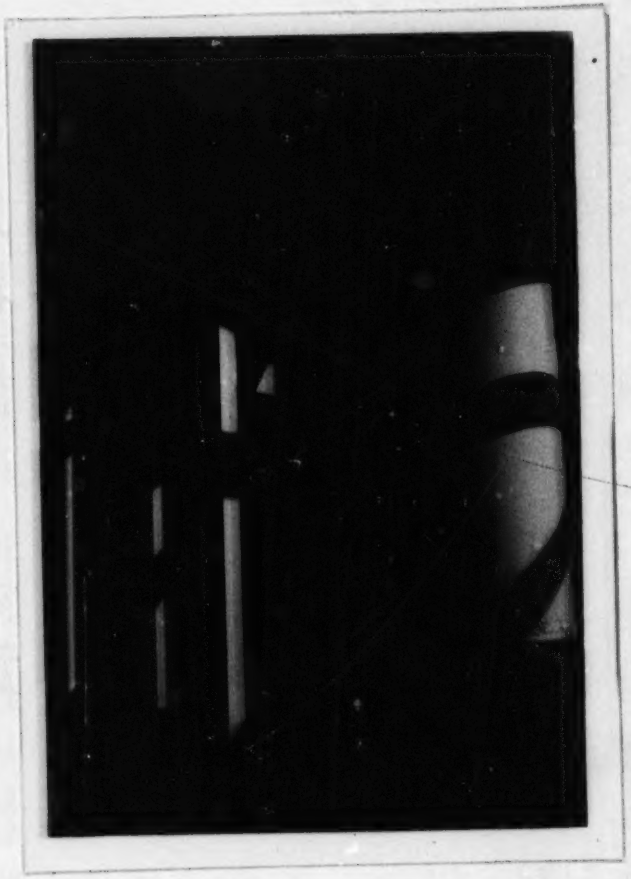

Figure 7. Inlet tubes showing alignment of collars.

After the inlet tube is bolted in place, the support poles for the shroud should be erected. These 5 cm x 5 cm aluminum posts are connected to the deck by 2 bolts and to the guard rail by 1 bolt. Next, connect the wind shroud to the aluminum posts. Shroud sections #1 and #3 should be erected first. Bolts are provided to connect the mounting flanges of each section to the posts (Figure 8). Sections #2 and #4 should be erected next and should slightly overlap sections #1 and #3 where they meet on the outside of the posts (Figure 9). After the shroud has been set up, the rain shield can be erected by inserting the shield's legs into the top of the aluminum posts (Figure 10). The shield is held in place by spring tensioned tiedowns (Figure 11).

Figure 8. Attachment of the shroud to the support poles (inside).

Figure 9. Attachment of the shroud to the support poles (outside).

Figure 10. Assembly of shroud and rain cap.

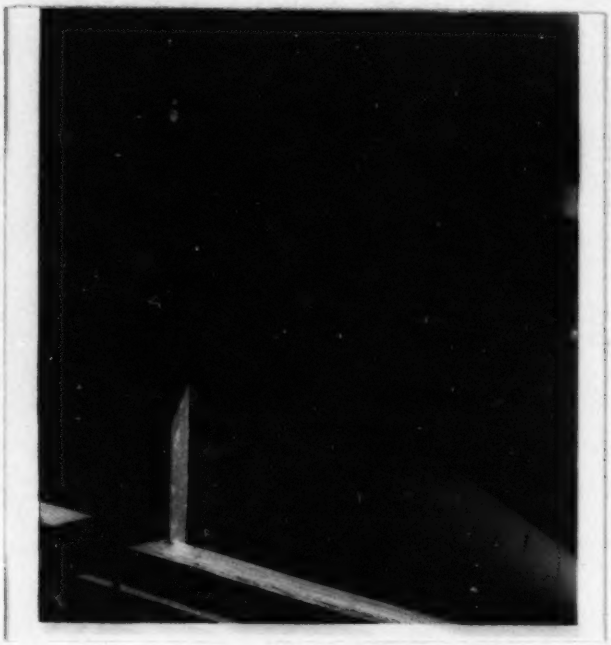

Figure 11. Assembly of shroud and rain cap tiedown.

SAMPLING PREPARATIONS

Sample filters and impaction plates should be prepared for use in the sampler. The stainless steel impaction plates should be spray coated and allowed to dry for 24 hours. A grease coating improves the particle collection efficiency of metal plates by preventing bounce off of hard particles. Drying time is allowed for the grease coating so that any solvent used in applying the grease has a chance to evaporate. The sampler uses standard 20.3 cm x 25.4 cm high volume air sampler filters as final filters after the impactors and for the total sampler. The filters should be of a neutral pH type to avoid sulfate particulate formation (25). Sampler filters and impaction plates should be equilibrated at a suitable reference condition (less than 50 percent

relative humidity and constant temperature) for at least 24 hours prior to initial or final weighing. An equilibration chamber was constructed in the analysis van which can accommodate several sets of filters and impaction plates.

A Mettler He-20 electromechanical semi-micro balance is provided in the analysis van for use in weighing the filters and plates. The He-20 is equipped with an enclosure attached to and below the balance weighing chamber in which to weigh the filters and impactor plates. A vibration damping platform is used with the He-20 to increase stability of the balance. It is recommended that the balance be switched on at least 1 hour prior to use to allow time for the electronic components to stabilize. It is not, however, good practice to leave the balance on continuously because the digital readouts will eventually burn out. Care should be taken to insure that the filters and impaction plates are always centered on the balance pan in the weighing chamber, as this will affect the weights determined. It is also important that the filters and plates should not be touched by hand during weighing because skin moisture will affect the weight. A pair of tweezers and a wire fork are provided for inserting and removing the filters and plates from the weighing chamber.

Once the filters and impactor plates are weighed, the sampler can be assembled. The impactor plates are slid onto the impactor plate supports and fastened into the impactor (Figures 12, 13, 14). Screws and a screwdriver are provided to secure the supports in the impactor body. The filters are placed on top of the filter holders which are then fastened under the impactor (Figure 15). After the sampling run, the filters and plates are removed from

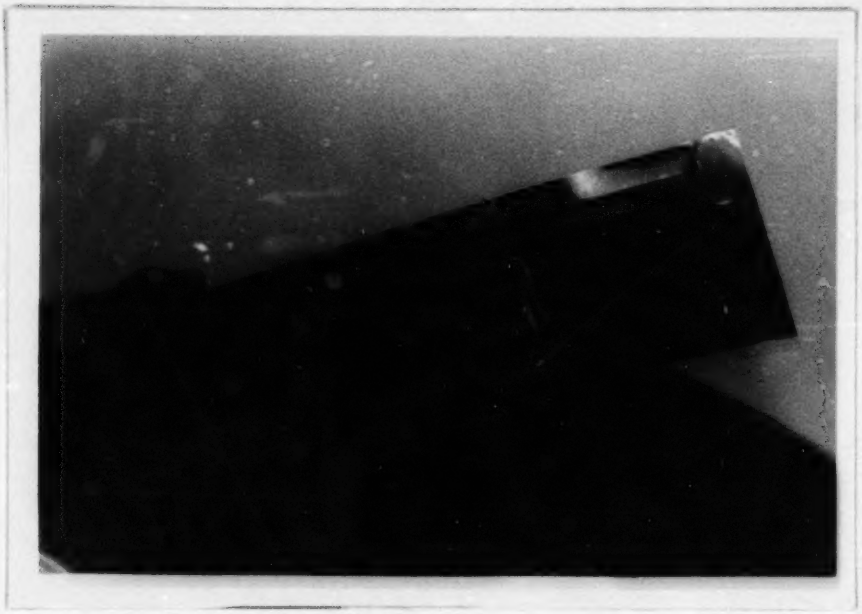

Figure 12. Impactor collection plates slide onto supports.

Figure 13. Impactor plates inserted into the impactor.

Figure 14. Impactor plates fastened into the impactor.

Figure 15. After filter on filter holder put into place.

the sampler and returned to the equilibration chamber in the analysis van. The filters and plates should be re-equilibrated for 24 hours and then weighed.

OPERATION

The auxiliary blowers and the size-selective sampler blowers are each controlled by a switch. These switches are mounted on the inside wall of the trailer and are labeled. The sampler blowers share a circuit breaker and should be started one at a time to avoid overloading the circuit due to starting current surges.

The size-selective sampler blowers are controlled by flow controllers which sense the flow through the samplers and control each blower through a feedback circuit (Figure 16).

The air flow rate through the size selective samplers is set by adjusting the flow controllers connected to each blower. To check the flow rate through the size-selective samplers, the velocity pressure can be measured by attaching a magnehelic to the pressure tap at the exhaust end of the sampler blower. These taps have been calibrated against a reference thin plate orifice.

The flow rate through the auxiliary blowers can be checked by measuring the pressure differential across the thin plate orifices. If the flow rate needs adjusting, this can be accomplished by tightening or loosening the screw clamps on the blower exhaust duct thus changing the duct exit area (Figure 17).

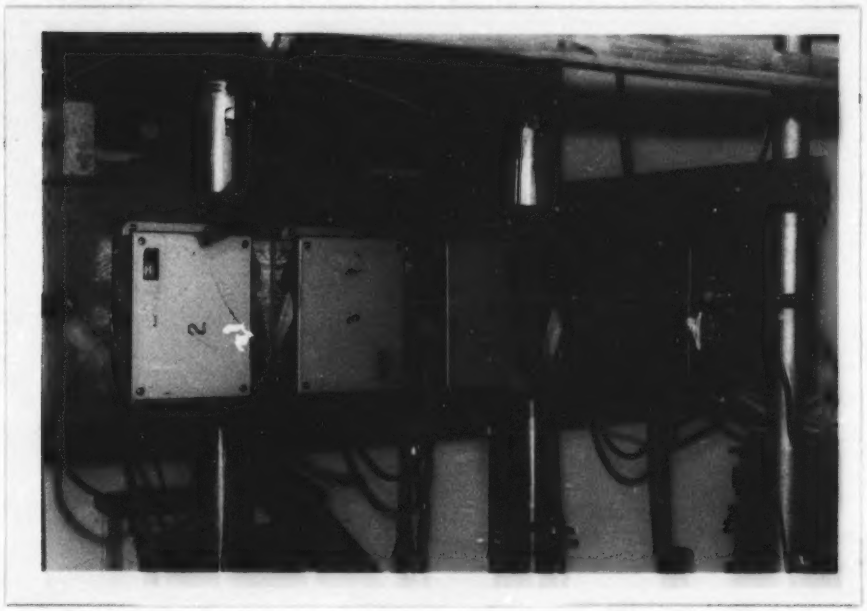

Figure 16. Flow controllers for sampler blowers.

Figure 17. Auxiliary blowers and pressure taps for the thin plate orifices.

The sample time can vary but is generally assumed to be about 24 hours. For heavy concentrations of atmospheric particulate matter, the sample time may be shortened.

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Dale A. Lundgren and David C. Rovell-Rixx of the University of Florida Department of Environmental Engineering Sciences are authors of the report "Wide Range Aerosol Classifier". They are also authors of the Project Summary.

R. M. Burton is the EPA Project Officer (See below).

The complete report, entitled "Wide Range Aerosol Classifier" (Order No.); Cost: , subject to change will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161
Telephone: 703/487-4650

The EPA Project Officer can be contacted at:

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